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FINAL REPORT

on

SONIC BOOM RESEARCH

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Principal Investigator: Lu Ting

NEW YORK UNIVERSITY
FACULTY OF ARTS AND SCIENCE
DEPARTMENT OF APPLIED SCIENCE

SUMMARY

Under this research grant, we studied the goals for future SST and demonstrated conclusively that we can design a supersonic airplane configuration weighing over half a million pounds while creating a maximum sonic boom of less than 1 p.s.f. which is well below the allowable limit. We designed new experimental techniques in the wind tunnel and carried out the experiments for the sonic boom measurements. We carried out theoretical analyses for the effects of sonic boom on structures. We investigated the pollution problems associated with supersonic flights. We generated numerical programs for the sonic boom propagations from the near field of an airplane in supersonic flight at high altitude to the ground taking into account the nonlinear effects and the asymmetric effects due to lift and the spacewise distributions of lift and volume.

BRIEF DESCRIPTION OF THE INVESTIGATIONS

Our investigations can be classified into six categories in accordance with their main objectives. They are: (i) goals for future SST, (ii) low sonic boom configurations, (iii) techniques for sonic boom measurements, (iv) sonic boom effects on structure, (v) pollution problems, and (vi) numerical programs for sonic boom propagations. We will describe the investigations for these categories one by one.

I. Goals for Future SST

Studies of the future transportation requirements project the need of airplanes having usable ranges up to 7000 n. mi. Since the cost per passenger mile increases substantially when the range of the airplane increases while the speed remains the same, subsonic airplanes are not too promising for ranges above 4000 n. mil. In addition, the duration of subsonic flight for such ranges becomes too long and uncomfortable. The cost and time factors weigh in favor of supersonic or hypersonic transports as reported in [1]. Recent prominent advances in aerodynamics, propulsion, structure design, material and fabrication criteria, which enhance substantially the performances of SST, were noted in [1]. The feasibilities of sonic boom reductions by optimum design of the airplane configurations and by flying at higher Mach number and at higher altitudes were discussed in [1].

In 1975 Dryden Research Lecturer, Dr. Ferri assessed the possibilities and goals for the future SST. The airplane requirements and corresponding technology improvements in new engine designs, structure weight improvements and aerodynamic drag reduction or the increase in L/D was reported. Recent investigations which clarify substantially the air pollution problems of SST

were reported. The objections by the environmentalists were shown to be inconclusive and in some cases to be incorrect. The need for a new criteria for acceptable sonic boom level and the substantial improvement in airplane configuration for sonic boom reductions were also reported. The recommendations and conclusions are [2].

"A long range SST is a logical and important development for the U.S.A. An airplane capable of carrying 300 passengers for ranges on the order of 7000 miles appears to be within the capability of advanced technology. Only a few of the several predictable technological advancements are required to reach such a goal. Such advancements can be reached by means of a well-focused research and development program. The main fields to be investigated are:

a) Propulsion. Rapid development of variable cycle engines and variable bypass engines should be performed.

b) Structural and airplane design. The use of augmented control techniques must be investigated in flight, and the use of advanced materials for structural components and corresponding new structural designs should be investigated in flight.

c) New advanced aerodynamic configurations, boundary-layer controls, and low sonic boom airplanes. Field measurements on sonic boom response should be performed as soon as the Tupolev and Concorde initiate operation.

d) Advanced accessories and service equipment. The goal of the effort is to save cost and weight.

e) Operational changes. A program in operations should be directed at improving airplane performance. These should be defined and systems required by such changes developed.

This program can be expensive; therefore, we should ask if the research and development program can be afforded. I am not an economist; however, I

have seen several studies of the SST performed by experts where economical analyses were presented. Such studies show that a substantially improved version of the SST, but, still less advanced than the one suggested here, would be economically sound. In these studies, no government support for the development cost was assumed. Therefore, I am confident that a detailed economical analysis of the approach described will give a satisfactory answer. The comparison of fuel consumption per passenger mile, given between the advanced SST and the 747, and the comparison of structural weight are already indications of the economical aspects of the problem. Because of the long-range implications for our nation and the world, I believe that this program is more important than other aeronautical programs directed to retrofiting or to developing lower fuel consumption short-range airplanes. An advanced SST gives us new important possibilities that surely will be required in the near future. I hope that the Congress and the nation will proceed urgently with such a research and development program."

II. Low Sonic Boom Configurations

Optimum configurations for low sonic boom research was carried out toward the definition of future configurations that can reduce the maximum over pressure without compromising too strongly other characteristics of the airplane. Several parameters affect the sonic boom, such as the weight of the airplane, altitude of flight, sizes, etc. In the analysis reported in [3] the only parameter considered as variable is the configuration of the airplane. In order to use realistic parameters in the analysis performed, a configuration proposed by industry for the supersonic airplane design has been used as a basis for comparison. The length of the airplane is kept constant and equal to 300 feet. The weight, altitude, and Mach number of flight are

kept constant and equal to 465,000 pounds and 60,000 feet and M = 2.70. The variations of configurations investigated must not affect the drag too much at the required lift at the flight Mach number. The conclusion of the analysis [3] is: "From these preliminary considerations, it appears that airplanes having lifting surfaces extended to the front of fuselage, and utilizing interference effects can be effective in reducing maximum sonic boom overpressure, because it utilizes near-field effects."

The basic concept of optimum lengthwise distribution of lift for low sonic boom was further exploited and the results were reported in [4]. The summary is: "Sonic Boom signatures produced by possible SST configurations during cruise have been investigated. It is shown that optimization based on a far-field analysis is not necessarily the optimum for these conditions. For an airplane length of 300 ft, near-field effects can be obtained when sufficient lift is generated near the nose of the airplane. Because of the near-field effects, sonic booms with maximum overpressures of the order of 1 lb/ft^2 can be obtained with possible airplane configurations having the same flight conditions at cruise."

Additional investigations for low boom airplane configurations were reported in [5]. The parameters investigated here are airplane configuration, weight, length, Mach number, and flight altitude. The criteria for the selection of the range of the parameters selected are outlined as follows: Three different values of weight have been considered corresponding either to horizontal flight or to maneuvers: 460,000, 320,000 and 240,000 lb. The first weight assumed is representative of the first part of cruise for an airplane takeoff weight of 600,000 lb. This airplane, with a payload of 50,000 lb, should be able to fly 4900 statute miles. The length of the airplane is a very important parameter to obtain near-field signatures; therefore, lengths

on the order of 300 to 400 ft have been considered. Few calculations have been performed for shorter lengths to emphasize the difficulty of obtaining near-field signatures for short airplane lengths. In addition, the available height of the airplane has also been utilized to increase the effective length of the airplane. The flight Mach numbers considered are 1.5, 2.7, and 4. An increase in cruise Mach number tends to decrease the fuel consumption per mile, and therefore for a given weight of the airplane, will permit a better compromise for the design from the sonic boom point of view because it will permit some degradation of aerodynamic performances.

Several flight altitudes have been considered between 40,000 and 80,000 ft. Another parameter that has been investigated parametrically is the shape of equivalent cross-sectional area distribution. To obtain realistic equivalent area distribution that could correspond to a possible airplane design, the equivalent area distribution has been divided into two regions, the front and rear. The important characteristic of the front and rear regions is defined mainly by two parameters: the area of the equivalent cross-sectional area in the front region and the length of the front region. The details of the distribution of the equivalent cross-sectional area in this region do not affect strongly the results provided that such a distribution is close to optimum. Therefore, in all of the analyses, the equivalent area distribution has been divided into two regions. The total value of the equivalent area and the length has been changed parameterically, while the form of the distribution has been kept constant.

The conclusion of this investigation [5] is: "The results of the analysis presented here indicate that from an aerodynamic point of view, it is possible to generate airplane configurations that can reduce substantially the strength of the front and tail shocks of sonic booms for airplanes designed for transatlantic operations: values as low as 0.5 lb/ft^2 are possible. Values as low

as 0.4 and 0.3 lb/ft^2 are possible when the weight is reduced for cross-country operations and the airplane is optimized for minimum sonic boom. These values are much lower than the values investigated in present flight tests and appear to be in the range of acceptable disturbance from extrapolation of present information on possible reaction to sonic boom. In addition, disturbances of the same order are presently accepted in normal operations in populated areas. The analysis presented here has treated only superficially the consequences of utilization of such concepts on airplane performances. The maximum L/D of the airplane at cruise should not be strongly affected by the change suggested. The structural weight, however, will probably increase with respect to simpler conventional solutions. Some increase in weight and decrease in L/D are acceptable for a shorter range airplane; in addition, small improvements in engine performances could make such deterioration acceptable. Therefore, the work required to analyze such configurations is justified. Two steps are required to proceed further: (1) the acceptance of such levels of disturbances should be determined by measuring the shape and level of present disturbances currently generated in city operations and by additional flight tests; and (2) the incorporation of such concepts in practical, usable configurations for second-generation SST's should be investigated.

A survey of investigations on the predication of sonic boom generation and the minimization of the sonic boom is presented in [6]. The status of present availability and lack of knowledge is reviewed and recent contributions are described.

The inadequacy of quasi-linear theory for sonic boom prediction for high Mach number flight and for caustic regions and the need for fully nonlinear analysis were pointed out. The difficulty of experimental measurements for

low "bang" configuration was emphasized and suggestions for new experimental techniques were provided.

The differences between far field asymptotic solution and the "near field solution" for "long" airplanes are emphasized and utilized to study low "bang" airplane configurations.

It was demonstrated that within the dimensions already accepted as practical for the SST configuration, sonic boom signatures have a Δp due to the front shock of the order of 1 lb/ft^2 are possible in principle. The configuration meets some of the requirements of an SST configuration such as volume, approximate value of drag, wing area, lift, and approximate balance. Such results indicate that the possibility of developing practical configurations that can produce sonic boom levels of this order should not be ignored.

Two designs for low "bang" configurations, which have 300 ft long fuselage, and the required wing for an airplane weighing 465,000 lbs flying at $M = 2.70$ at an altitude of 65,000 ft, are presented.

The sonic boom shape, after the waves are reflected on the ground, has been calculated for such airplanes. The front and rear bangs have a Δp of the order of 0.6 lb/ft^2. The equivalent length of the airplane from a sonic boom point of view is of the order of 490 ft. This value takes into account the height of the airplane and the jet exhausts.

The small negative angle of attack of the fuselage penalizes the drag of the airplane for an amount that is less than 1/100 of the drag of the airplane at cruise.

The main purpose of these analyses is to prove that by a careful selection of all parameters involved it is possible to design an airplane configuration

having 300 ft fuselage, that at cruise produces sonic booms that have "bangs" below 1 lb/ft^2. These results justify work on configuration design to define the amount of compromise in performance, if any, which is required to accomplish these goals. In addition, substantial effort is urgently needed to better define practical acceptable levels of sonic "bangs".

III. Experimental Determination of Sonic Boom in Wind Tunnel

The determination of sonic boom signatures for complex models requires experimental data. Usually when the sonic boom is determined analytically, the strength of the disturbances that determine the signature is obtained on the basis of linear approximation. Even for linear theory, interference effects are sometimes difficult to analyze. On the contrary, an experimental determination of the sonic boom at some distance from the model, where disturbances are small, permits extrapolation of the signature at large distances from the model by means of the Whitham theory without the introduction of additional approximations above that given by this theory.

A correct method of extrapolation from one distance to another requires that the distribution of disturbance be determined either on a surface, for example, a cylinder that surrounds the model at some distance from the model, or at a surface that is a stream surface of the flow obtained by intersecting the flow field with an infinite plane parallel to the undisturbed velocity. The disturbances at these surfaces can be substituted for the body. At these surfaces the disturbances are small, thus the analysis can be applied correctly.

While this approach is the only theoretically correct one, it is difficult to use because it requires the determination of a complete stream surface; therefore, in many experiments the assumption that the flow around the body

can be represented by an equivalent axially symmetric body placed at the position of the model is introduced. Then the signature needs to be determined only along a line. From this signature, the signature at other distances can be obtained. This approach is not completely satisfactory when the supersonic leading edges are present. In addition, when large nonlinear effects are present, the signature does not lead to an F-function at the axis of the body. Often, other problems of a practical nature are present that affect strongly the precision of the results. These practical problems are outlined in [7]. The effects discussed herein are

(1) Support interference

(2) Uniformity of flow

(3) Difficulties at high Mach numbers

(4) Reynolds number effects.

The conclusion of the paper [7] is: "The use of experimental data permits obtaining sonic boom signatures at some distance from the body when the theory applies. However, wind tunnel irregularities and support interference can influence the results unless these effects are taken into consideration. Three-dimensional effects can be important."

Because of practical experimental difficulties, distances from the model of the station where measurements are performed cannot be too large. The precision of the measurements decreases sharply with an increase of distance because of the finite sensitivity of the instruments. Furthermore, the size of available wind tunnels and the size of the model required for the tests limits the ratio between distance of measurements and length of the model. Another important difficulty is due to the fact that the flow field produced by a wind tunnel is not absolutely uniform. In any wind tunnel, nonuniformity of a few percent in Mach number exists. Such nonuniformities correspond to waves that interact with the wave pattern produced by the model. When these

disturbances interact with the flow field, an error is introduced that is cumulutative along the waves carrying disturbances from the model to the plane of measurement. The strength of the waves that is produced by the model at a very large distance from the model is only slightly larger than the waves due to nonuniformities existing even in the most uniform wind tunnel. Therefore, the error introduced is proportionally larger at larger distances. This error tends to increase with Mach number. Thus, a compromise must be reached between accuracy required and distance of the measurement where a single measurement is acceptable.

The problem can be reduced substantially by the introduction of more complex techniques for obtaining experimental data, and extrapolating the results. Two different approaches have been proposed [8] where the measurements are performed in a plane located at some distance from the model parallel to the plane where the sonic boom signal must be determined. The deviations of the stream surface normal to the plane are measured in a region inside the shock generated by the front tip of the airplane. Such deviations are determined along several straight lines parallel to the flow direction to cover all of the flow inside the shock. A stream surface is defined by the measurements that can be substituted for the airplane. Such a stream surface where the flow disturbances are small is equivalent to the vehicle placed above. Then, the Whitham analysis as applied by Walkden, is used directly to determine sonic boom at the required distance from this surface. The precision of this method depends on the compromise of two opposite requirements: (1) the accuracy of the linearized theory which increases with the distance from the body; and (2) the precision of measurements which decreases when the distance increases. However, three-dimensional effects are accounted for accurately. The experiments presented in [8] tend to indicate that a satisfactory compromise can

be obtained for these two opposite requirements even if the measurements are performed at rather small distances from the body.

Experiments have been performed by and reported in [8] by using the second method, in which, the streamline deviation is measured for several streamlines starting on a cylindrical tube placed around the model having the axis parallel to the wind, and at small distances from the axis. In the experiments performed, the distance is smaller than the length of the model. The deviation of each streamline of this tube is measured locally in several meridian planes. Two angles are measured: one gives the deviation in the meridian plane; and the second gives the deviation on the cylinder normal to the meridian plane. These data are used to determine at the axis of the cylinder the F-function that is used in the Whitman theory, by means of higher order approximation that takes into account second order terms in the disturbance components and higher order terms in the curvature according to a theory developed by the proposers of the method.

This method permits us to use smaller distances from the models than the other; however, it requries differentiation of the measured deviation which is difficult to do. In addition, the analysis assumes that the three-dimensional and thickness effects are small so that the disturbances can be extrapolated at the axis of the body. This last condition can produce F-functions that are not singly valued. Both approaches are improvements with respect to the standard method, especially at Mach numbers of 2 or 3.

The experimental investigation performed permits us to reach the following conclusions:

1. Sonic booms having peak values of the order of 1 lb/ft^2 as predicted analytically in reference 3 have been measured.

2. The nonlinear and three-dimensional effects are of primary importance for the determination of the correct values of the sonic boom from measurements at small distances from the model.

3. More complex experimental techniques where such effects are determined are required when near field measurements are made.

4. The second experimental method gives satisfactory results.

5. Improvements are still required in the experimental techniques and in the analysis in order to measure and determine with better accuracy all of the required quantities.

IV. Sonic Boom Effects on Structures

The diffraction and reflection of plane wave, an N-wave, by a two dimensional structure in the form of a rectangular block have been analyzed. The pressure variations on the walls of the structure are obtained. The results were reported by Ting and Pan [9]. The summary of the article is:
"When an N-wave hits a structure, two aspects of the reaction are of interest. One is the intensification factors and the locations where the transient pressure variation becomes a maximum. The other is the assessment of the transient load or pressure distribution on the structure. The transient maximum pressure rises usually occur at a concave corner facing the incident N-wave. The intensification factor at the corner in certain instances can be determined directly by making use of the reflection principle, the conical solution, or the averaging principle without the knowledge of the solution to the entire flow field even its neighborhood. However, for the determination of the transient load on the structure, it is necessary to obtain the history of the pressure distribution on the structure.

A procedure for the determination of the transient pressure distribution on a two-dimensional structure in the shape of a rectangular block by an incident N-wave is presented. It is the superposition of the solution of a unit plane pulse incident on the structure. When the plane pulse hits the first convex corner, the pressure distribution is given by a conical solution. When the conical flow field propagates to the next convex corner, the diffracted flow field, which is no longer conical, is obtained by the method developed for the diffraction at a convex corner propagates to its adjacent convex corner. A numerical program is developed to compute the pressure distribution on the two-dimensional structure incident by a plane pulse or by an N-wave.

The problem of an N-wave incident on a three-dimensional structure is very complicated. Even the basic conical solution of a plane pulse incident on the corner of a cube is not yet available. It is shown that the transient intensification factors at several corners of a three-dimensional structure are computed when the averaging principle is applicable."

The canonical three-dimensional problem of the diffraction of a weak shock wave by a corner in the form of a vertex of a cube was analyzed by Ting and Kung. An outline of the analysis was reported [10]. The summary is: "For the three-dimensional problem of the diffraction of sonic boom by structures, the first step is the construction of the solution for the diffraction of a plane pulse by a corner of a structure. By the decomposition of an N-wave to plane pulses, the solution for the diffraction of an N-wave by a corner can then be constructed. The results presented here contain the highlights of two subsequent papers. One deals with the construction of three-dimensional conical

solution and the other deals with the use of the conical solution for the computation of pressure distributions on the surfaces due to a N-wave of any waveform and at any incident angle. Both papers contain detailed analyses and the relevant numerical programs."

Procedures for the construction of the conical solution to the canonical problem and the numerical program for the computation of the eigenvalues and the eigen functions are reported in detail in [11]. The summary is: "For the diffraction of a pulse by a three-dimensional corner, e.g., the corner of the cube, the solution is conical in three variables $\zeta = r/(Ct)$, θ and ψ. The three-dimensional effect is confined inside the unit sphere $\zeta = 1$, or the sonic sphere $r = Ct$ with the vertex of the corner as the center. The boundary data on the unit sphere is provided by the appropriate solutions for the diffraction of a pulse by a two-dimensional wedge. The solution exterior to the corner and inside the unit sphere is constructed by the separation of the variable ζ from θ and ψ. The associated eigenvalue problem is subjected to the same differential equation in potential theory for the spherical angle variables θ and ψ, but with an irregular boundary in $\theta - \psi$ plane. A systematic procedure is presented such that the eigenvalue problem is reduced to that of a system of linear algebraic equations. Numerical results for the eigenvalues and functions are obtained and are applied to construct the conical solution for the diffraction of a plane pulse. For the diffraction of a general incident wave by corners or edges, the solutions are no longer conical. Two theorems are presented so that the value at the vertex of the corner or along the edges can be determined without the construction of the-three dimensional non-conical diffraction solutions. Relevant numerical programs

for the analysis are presented in the appendix."

The extension of the analysis to handle different boundary conditions on the surfaces of the corner and to treat the incidence of a plane wave of general wave form is reported in [12]. The summary is: "The conical solutions for the incidence of a plane pulse on a three-dimensional corner are presented. The corner is represented by a trihedron with one edge perpendicular to the other two. Both the boundary condition of the first kind $p = 0$, and that of the second kind, $\partial p/\partial n = 0$, are considered. Outside the characteristic sphere of the vertex of the corner, the solution is represented by the well known conical solutions in two variables. Inside the characteristic sphere, the problem involves three conical variables. By the separation of variables, the problem is reduced to that of an eigenvalue problem with an irregular boundary which is in turn reduced to a system of homogeneous algebraic equations. The eigenvalues are then determined numerically. By the superposition of the conical solutions for plane pulses, the solution for the incidence of a plane wave is obtained. Numerical examples simulating the incidence of a sonic boom on the corner of a structure are presented."

The application of theoretical analyses of the preceding three papers to the problem of the incidence of an N-wave through an open window (a rectangular opening) to the interior of a room is presented in [12]. The summary is: "The problem of diffraction and reflection of a plane pulse, such as the bow shock of the sonic boom produced by SST airplane, by rectangular openings, such as windows, is solved by use of Bernoullis Separation method in three variables $\zeta = (x^2 + y^2 + z^2)^{1/2}/Ct$, θ and ψ. The three-dimensional effect is confined inside the unit sphere $\zeta = 1$ or the sonic sphere $r = Ct$ with the

corners of the opening as center. The solution exterior to the corner and inside the unit sphere is constructed by the separation of variable ζ from θ and ψ. The associated eigenvalue problem is subjected to the same differential equation in potential theory. A systematic procedure is presented such that the eigenvalue problem is reduced to that of a system of linear algebraic equations. Numerical results for the eigenvalues and functions are obtained and are applied to construct the conical solution for the diffraction of a plane pulse through a rectangular opening in a plane."

Theorems which provide the intensification factor along the edges and vertices of a structure due to an incident wave and reported in [14]. The summary is: "The spherical means of the solutions of a linear partial differential equation Lu = f in a conical region are studied. The conical region is bounded by a surface generated by curvilinear ξ lines and by two truncating ξ surfaces. The spherical mean is the average of u over a constant ξ surface. Conditions on the linear differential operator, L, and on the orthogonal coordinates ξ, η, ζ are established so that the problem for the determination of the spherical mean of the solution subjected to the appropriate boundary and initial conditions can be reduced to a problem with only one space variable. Conditions are then established so that the spherical mean of the solution in one conical region will be proportional to that of a known solution in another conical region. Applications to various problems of mathematical physics and their physical interpretations are presented."

V. Pollution Problems

The possibility that the exhaust gases of a supersonic transport could severely shift the equilibrium of the stratosphere, so altering the balance of ozone formation, proved one of the powerful arguments presented against the plan to develop such an aircraft in the United States. No

scientist brought forward real proof or satisfactory laboratory experiments to support this claim. Nevertheless, opponents of the SST successfully exploited it. Now, scientists have generated new technical information that allows us to assess this supposition better.

Research now shows that some of the chemical effects related to the production of water vapor by an SST engine, assumed to be important initially, are actually not important; and, as a consequence, although much remains to be understood, the SST engine can now be investigated in terms of acceptable levels of nitrogen oxides and appropriate specifications for engine design. as in other pollution problems. This is explained in detail in [15]. The conclusion is: "The results support the expectation that, if necessary, oxides of nitrogen from an SST at cruise can be reduced substantially. Discussions concerning effects of these oxides on ozone reduction should thus use two sets of data -- one corresponding to present engine designs, which produce of the order of 400 parts per million of oxides of nitrogen in the exhaust gas, and the other corresponding to possible future engine designs, which can have values of the order of 1 or 2 parts per million. The reduction by a factor of 400 probably will make a substantial difference in any tentative conclusion reached at a given state of the investigation."

A qualitative review of the possible effects of the exhaust gases discharged by a large fleet of SST's in the upper atmosphere is represented in [16]. The review indicates the importance of the NO production in the exhaust gases. The mechanism of NO formation is presented. The conclusion is: "Recent available information on the interaction of the exhaust gases discharged by

airplanes with the upper atmosphere tends to indicate that important chemical effects can be produced. The effects are important, when large fleets of airplanes fly in the stratosphere where the residence time is long. It is presently believed that these effects are due mainly to the formation of nitric oxide and SO_2. The sulphur can be removed from the fuel at a small cost. The NO_x can be reduced by a factor of 50 if required by changes in the combustor designs. Then the danger of large effects can be eliminated even if a substantial number of airplanes are utilized. More detailed conclusions will be obtained from the CIAP study. The time involved in the production of a large fleet of airplanes is large; therefore, time is available to perform more accurate evaluation of all the aspects of the problem and to introduce the required changes in the burner if required."

The potential seriousness of SST pollution problems has motivated a major national effort to develop a better quantitative understanding of the phenomena involved. Recently two reports gave assessments of our knowledge: 1) DOT/CIAP Final Report, "The Effects of Stratospheric Pollution by Aircraft", by Alan J. Grobecker, S.C. Coroniti, and R. H. Cannon Jr., DOT-TST-75-50, December 1974, and 2) National Academy of Sciences, "Environmental Impact of Stratospheric Flight - Biological and Climatic Effects of Aircraft Emissions in the Stratosphere," 1975.

The conclusions of these two independent reports and their implications were discussed in [17]. Many new questions and the directions for additional research effects were pointed out.

VI. Numerical Programs for Sonic Boom Propagations

For airplanes flying at high Mach number, say 4 to 8, and at high altitude, its numerical program for sonic boom analysis under the freamework of Whitman's theory is inadequate because it ignores the higher order nonlinear terms and the entropy terms. The accumulations of these terms over a long distance of propagation may become significant. A new numerical program is developed to include all the nonlinear terms in the differential equation and the shock conditions. The results are reported in [18]. The summary is: "A nonlinear characteristic program for quasi-axisymmetric flow has been completed which includes nonlinear effects induced by a stratified atmosphere, the variation of entropy across shock waves, rotationality in the flow, the curvature of the characteristics, and the effect of both families of waves. The numerical results show that these highly nonlinear terms can be important for high-Mach-number, high-altitude flight and for complex configurations, especially in the prediction of rear shock waves. For optimum sonic boom considerations, it is desired to redistribute the volume and lift in such a manner that the first boom is reduced and successive booms will be of the same order or slightly larger; therefore, an accurate prediction of the rear shock is of importance in design considerations. A procedure to include the effect of asymmetry due to airplane configuration and a stratified atmosphere also has been presented." A detailed description of the analysis is presented in the Ph. D thesis of M. Siclari [19].

In the preceding analyses, the flow field is assumed to be axi-symmetric with respect to the axis of the body. This assumption is not realistic because an airplane configuration has to create lift. Since the sonic boom signature is important only near the vertical plane of symmetry a numerical program to take into account the asymmetric effect near the vertical plane

of symmetry is developed. The results are reported in [20]. The summary is: "A numerical program is developed which takes into account the nonlinear effects of high Mach number, the entropy change across the shock, the entropy and enthalpy variations in the atmospheric layer and the gravitational effect. The program differs from the existing ones by accounting for nonaxisymmetric terms. The asymmetry can be caused by the geometry of the body, the lift, and also the fact that the variations in the atmospheric layer are two dimensional. Numerical results demonstrate that the influence of these asymmetric effects tends to lower the pressure signature."

The numerical program [21] which includes the asymmetric effect due to lift was delivered to the contract in June 1976. An extension of the numerical program to include the effects due to spanwise distributions of lift and volume was completed and delivered to the contractor in October 1978. A separate program which prepares the input data of these sonic boom programs from the near field experimental data will be delivered to the contractor in January 1979.